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APPLICATION ELEMENTS

See MPEP chapter 600 concerning utility patent application contents.

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2. X Specification (Total Pages 55)
(preferred arrangement set forth below)
 - Descriptive Title of the Invention
 - Cross References to Related Applications
 - Statement Regarding Fed sponsored R & D
 - Reference to Microfiche Appendix
 - Background of the Invention
 - Brief Summary of the Invention
 - Brief Description of the Drawings (if filed)
 - Detailed Description
 - Claims
 - Abstract of the Disclosure
3. X Drawings(s) (35 USC 113) (Total Sheets 11)
4. X Oath or Declaration (Total Pages 5)
 - a. Newly Executed (Original or Copy)
 - b. Copy from a Prior Application (37 CFR 1.63(d))
(for Continuation/Divisional with Box 17 completed) (**Note Box 5 below**)
 - i. DELETIONS OF INVENTOR(S) Signed statement attached deleting inventor(s) named in the prior application, see 37 CFR 1.63(d)(2) and 1.33(b).
5. Incorporation By Reference (useable if Box 4b is checked)
The entire disclosure of the prior application, from which a copy of the oath or declaration is supplied under Box 4b, is considered as being part of the disclosure of the accompanying application and is hereby incorporated by reference therein.
6. Microfiche Computer Program (Appendix)

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UNITED STATES PATENT APPLICATION

for

MULTISCALE SHARPENING AND SMOOTHING WITH WAVELETS

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MULTISCALE SHARPENING AND SMOOTHING WITH WAVELETS

FIELD OF THE INVENTION

The present invention relates to the field of data and image processing; more particularly, the present invention relates to performing sharpening and smoothing on multiple scales, or levels, of a decomposition of a signal or image.

BACKGROUND OF THE INVENTION

Sharpening and smoothing is fundamental to image enhancement and restoration. Image enhancement refers to accentuation of features of an image such as edges, boundaries, or contrast, and includes noise reduction, edge crisping and sharpening, filtering and many often well-known processes. Image restoration usually involves filtering an observed image to minimize, as best as possible, the effort of degradation. See A.K. Jain Fundamentals of Digital Image Processing, and W. Pratt, Digital Image Processing. Sharpening and smoothing are commonly used techniques in digital photography and scientific and medical imaging.

A popular sharpening method is referred to as unsharp masking which filters the image with a special highpass filter. A disadvantage of unsharp masking is that noise in the image is also sharpened and that the resulting output often looks "unnatural" since the choice of the appropriate degree of sharpening is difficult.

There exist many sharpening filters for image processing. These sharpening filters magnify the edges in an image, typically by highpass-filtering of the original image. A common method is unsharp masking as described in, for example, "Fundamentals of Digital Image Processing," by A.K. Jain, Prentice Hall, 1989.

In unsharp masking, given an image $f(x)$, a sharpened image $f_{\text{sharp}}(x)$ is obtained by adding a magnified gradient image to a smoothed ("unsharped") version of the image, i.e.

$$f_{\text{sharp}}(x) := f_{\text{smooth}}(x) + \lambda f_{\text{gradient}}(x) \quad (1)$$

where $\lambda > 1$ is the sharpness parameter. The sharpness increases with increasing λ . If the image $f(x)$ can be written as a sum of a lowpass filtered image f_{low} and a highpass filtered image f_{high} then Eq.(1) can be expressed as

$$f_{\text{sharp}}(x) = f_{\text{low}}(x) + (\lambda - 1) f_{\text{high}}(x). \quad (2)$$

In this approach the lowpass and highpass filters are fixed. One problem with this approach is that a priori it is not known what filter size, filter coefficients, and what value for the parameter λ is appropriate. If λ is too large, the image looks unnatural. To overcome this problem, some approaches apply several filters and take that output which looks most "natural" (see e.g., "Real World Scanning and Halftones," Peachpit Press, Inc., Berkeley, 1993 by D. Blatner, S. Roth).

In order to overcome the problem of sharpening not only "real" edges, but also noise pixels, the approach in "Adaptive Unsharp Masking for Contrast Enhancement," in Proceedings of the 1997 International

Conference on Image Processing (ICIP '97), pp. 267-270, 1997, by A. Polesel, G. Rampoui and V.J. Mathews, adds an adaptive directional component to an unsharp masking filter in the pixel domain that changes the sharpening parameter depending on strength and orientation of an edge. The unsharp
 5 masking filter is a two-dimensional Laplacian.

As mentioned above, the unsharp masking technique raises the problem of determining the degree of sharpening of an image that is best (i.e., finding the correct amount of sharpening). One solution to this problem is addressed in U.S. Patent No. 5,867,606, entitled "Apparatus and
 10 Method for Determining the Appropriate Amount of Sharpening for an Image," issued February 2, 1999, assigned to Hewlett-Packard Company, Palo Alto, California, for using the Laplacian in the unsharp masking technique. As a solution the magnitude of the sharpening parameter λ is determined by matching the Fourier spectrum of the sharpened image with
 15 a spectrum of a low resolution version of the original image. This requires in addition to the unsharp masking filters, a Fourier transform on the original image which has a higher computational complexity than a discrete wavelet transform. Furthermore, only one lower resolution image is incorporated into the technique.

20 The problem of enhancing a scanned document, such as, sharpening of scanned images in the JPEG domain is discussed in "Text and Image Sharpening of Scanned Images in the JPEG Domain," Proceedings of the 1997 International Conference on Image Processing (ICIP '97), pp. 326-329,

1997 by V. Bhaskaran, K. Konstantinides and G. Beretta. One proposed solution consists of a scaling of the encoding quantization tables to enhance high frequencies. The amount of scaling depends on the energy contained in the corresponding DCT coefficients. Since DCT functions form only a basis in $L^2(\mathbb{R})$, but not in more sophisticated smoothness spaces as, e.g., Hoelder spaces $C^\alpha(\mathbb{R})$, JPEG compression introduces blocky artifacts, a well-known problem in JPEG-compressed images. Those artifacts can be even magnified by scaling the DCT coefficients.

Wavelet coefficients have been modified for the purpose of contrast enhancement in images using criteria such as minimizing the mean-squared-error. However, these approaches do not consider the theoretical smoothness properties of an image in terms of local regularity and are computationally more complex.

In the prior art, detail versions of the image have been processed. Such an approach is described in U.S. Patent No. 5,805,721, "Method and Apparatus for Contrast Enhancement," issued September 8, 1998, assigned to Agfa-Gevaert, Belgium. In this approach, the image is decomposed into detail images at different resolutions and a lowpass image. This decomposition is not a subband decomposition, but a Laplacian pyramid where the reconstruction process consists of simply adding detail and lowpass images. The detail coefficients are multiplied with factors that depend on the magnitude of wavelet coefficients. This multiplication can be described by evaluating a monotonic function. This function has power-law

behavior, but does not change over scales. In a renormalization step, the pixels in the detail images are first normalized by the possible maximum of the pixels in the detail images. There is no discussion on how to choose the parameter contained in the monotonic function.

- 5 Modifications of wavelet coefficients have also been made based on energy criteria. For example, contrast enhancement in images by modifying wavelet coefficients based on energy criteria is described in "De-Noising and Contrast Enhancement Via Wavelet Shrinkage and Nonlinear Adaptive Gain," Proceedings of the SPIE, Vol. 2762, pp. 566-574, Orlando, Florida, 1996 by X. Zong, A.F. Laine, E.A. Geiser and D.C. Wilson. One problem
- 10 with this approach is that many computations are required because a comparison of local energy is performed for each individual wavelet coefficient. Furthermore, the modifications only apply to critically sampled wavelet transforms.
- 15 Embodiments of the present invention avoid or overcome one or more of the above mentioned problems.

SUMMARY OF THE INVENTION

A method and apparatus for processing image data are described. In one embodiment, a method of processing image data comprises decomposing the image data into multiple decomposition levels by applying a wavelet transform to the image data, and modifying coefficients in at least two of the decomposition levels by scaling coefficients in these decomposition levels using different scale dependent parameters for each of the decomposition levels.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention will be understood more fully from the detailed description given below and from the accompanying drawings of various embodiments of the invention, which, however, should not be taken
5 to limit the invention to the specific embodiments, but are for explanation and understanding only.

10 **Figure 1** illustrates one embodiment of a method for processing image data.

Figure 2 illustrates another embodiment of the process for processing image data.

15 **Figure 3** illustrates a block diagram of filter bank implementation of the first level of multiscale unsharp masking with a discrete wavelet transform.

20 **Figure 4** illustrates another block diagram of a filtering implementation of the first level of multiscale unsharp masking with an overcomplete discrete wavelet transform.

Figure 5 illustrates a flow chart of one embodiment of the process for performing multi-scale sharpening and smoothing with wavelets.

Figures 6A-D illustrate forward and reverse transforms.

Figures 7A-D illustrate the application of sharpening/smoothing to
5 RDWTs.

Figure 8 is a block diagram of one embodiment of a copier.

60727-419/9160

DETAILED DESCRIPTION

A multiscale sharpening and smoothing technique with wavelets is described. In the following description, numerous details are set forth, such as specific filters, etc. It will be apparent, however, to one skilled in the art, 5 that the present invention may be practiced without these specific details. In other instances, well-known structures and devices are shown in block diagram form, rather than in detail, in order to avoid obscuring the present invention.

Some portions of the detailed description which follow are presented 10 in terms of algorithms and symbolic representations of operations on data bits within a computer memory. These algorithmic descriptions and representations are the means used by those skilled in the data processing arts to most effectively convey the substance of their work to others skilled in the art. An algorithm is here, and generally, conceived to be a self- 15 consistent sequence of steps leading to a desired result. The steps are those requiring physical manipulations of physical quantities. Usually, though not necessarily, these quantities take the form of electrical or magnetic signals capable of being stored, transferred, combined, compared, and otherwise manipulated. It has proven convenient at times, principally for

reasons of common usage, to refer to these signals as bits, values, elements, symbols, characters, terms, numbers, or the like.

It should be borne in mind, however, that all of these and similar terms are to be associated with the appropriate physical quantities and are merely convenient labels applied to these quantities. Unless specifically stated otherwise as apparent from the following discussion, it is appreciated that throughout the description, discussions utilizing terms such as "processing" or "computing" or "calculating" or "determining" or "displaying" or the like, refer to the action and processes of a computer system, or similar electronic computing device, that manipulates and transforms data represented as physical (electronic) quantities within the computer system's registers and memories into other data similarly represented as physical quantities within the computer system memories or registers or other such information storage, transmission or display devices.

The present invention also relates to apparatus for performing the operations herein. This apparatus may be specially constructed for the required purposes, or it may comprise a general purpose computer selectively activated or reconfigured by a computer program stored in the computer. Such a computer program may be stored in a computer readable

storage medium, such as, but is not limited to, any type of disk including floppy disks, optical disks, CD-ROMs, and magnetic-optical disks, read-only memories (ROMs), random access memories (RAMs), EPROMs, EEPROMs, magnetic or optical cards, or any type of media suitable for storing electronic
5 instructions, and each coupled to a computer system bus.

The algorithms and displays presented herein are not inherently related to any particular computer or other apparatus. Various general purpose systems may be used with programs in accordance with the teachings herein, or it may prove convenient to construct more specialized
10 apparatus to perform the required method steps. The required structure for a variety of these systems will appear from the description below. In addition, the present invention is not described with reference to any particular programming language. It will be appreciated that a variety of programming languages may be used to implement the teachings of the
15 invention as described herein.

Overview

Techniques for multiscale sharpening and smoothing of data with wavelets, such as image data, are described herein. The multiscale
20 sharpening and smoothing techniques described herein, also referred to as

multiscale unsharp masking, provides an alternative to the prior art methods described above and is simple to implement. This approach uses the smoothness properties of wavelet systems to provide the sharpening and smoothing.

- 5 Specifically, the techniques described herein sharpen and smooth images over various levels of resolutions using a new sharpening/smoothing parameter. In one embodiment, the multiscale sharpening and smoothing is implemented in a wavelet decomposition by multiplying wavelet coefficients with a scale-dependent parameter. Figure 1
- 10 illustrates one embodiment of a method for processing image data. The method is performed by processing logic, which may comprise hardware, software or a combination of both. Referring to Figure 1, the process begins by decomposing the image data into multiple decomposition levels by applying a wavelet transform to the image data (processing block 101). The
- 15 transform that is applied to the image data may comprise, for example, a critically sampled discrete wavelet transform, an overcomplete discrete wavelet transform, a complex wavelet transform, a critically sampled or overcomplete wavelet packet transform. In one embodiment, the image data is transformed into multiple decomposition levels using a critically
- 20 sampled transform for selected subbands an overcomplete transform in others.

Then, after performing the decomposition, the process modifies coefficients in multiple decomposition levels by scaling coefficients in those

decomposition levels using different scale, or level, dependent parameters for each of the decomposition levels (processing block 102). For example, where scaling two levels, each coefficient in one of the decomposition levels is multiplied by a first scale dependent parameter and each coefficient in another of the decomposition levels is multiplied by a second scale dependent parameter.

In one embodiment, each of the different scale dependent parameters is determined according to the following formula:

$$\mu_j = 2^{j\alpha} \quad (3)$$

where the value of α (positive or negative) indicates whether sharpening or smoothing is applied to coefficients and j indicates the particular scale (level). In one embodiment, sharpening is applied to coefficients if α is less than zero and smoothing is applied to coefficients if α is greater than zero. Thus, if μ_j is greater than 1, then the result of the scaling operation is smoothing, while if μ_j is less than 1, then the result of the scaling operation is sharpening. The rescaling is applied only to wavelet (detail) coefficients, not scaling coefficients. In order to preserve the total energy of the image, a renormalization of the wavelet coefficients may be necessary.

In one embodiment, the scale dependent parameter is selected based on knowledge of the image data. That is, information extracted directly from the image can be incorporated in the choice of the sharpening or smoothing parameter. For example, knowledge that the input data indicates step edges may be used to select the sharpening or smoothing parameter.

Knowledge of the source of the image, e.g., scanner, may also be the basis of the selection of the sharpening or smoothing parameter. For example, this knowledge could be information on the point spread function in a scanner or other image source. In still another embodiment, the scale dependent parameter may be selected based on a monotonic function. The scale dependent parameter may be selected based on an estimate of the decay of wavelet coefficients across scales.

Referring back to Figure 1, after performing the multiscale sharpening and/or smoothing, processing logic performs an inverse transform on scaled (and unscaled) coefficients (processing block 103).

This technique may be combined with other wavelet-based image processing methods such as, for example, denoising. That is, multiscale sharpening and smoothing may be combined with other image processing steps in the wavelet domain. It has been shown in many applications that wavelet denoising is successful because edges are kept sharp whereas the noise is removed in smooth regions. This denoising can be simply done by thresholding wavelet coefficient. Suitable thresholding techniques include hard and soft thresholding. See, for example, Donoho, D.L. "De-noising by Soft-Thresholding, IEEE Trans. Inform. Theory, 41(3):613-627, 1995.

In one embodiment, simultaneously denoising and sharpening may be performed on wavelet coefficients by multiplying all coefficients above a predetermined threshold by a scaling parameter and setting all coefficients in the same decomposition level below a threshold to zero or to a value near

zero. In one embodiment, all the values of coefficients are reduced by a predetermined amount that might be given by a monotonic function. The resulting coefficients are then multiplied with the scale dependent parameter.

5 In the presence of random White Gaussian Noise, one advantage of the combined denoising and sharpening/smoothing technique is that the denoising threshold can be computed directly from wavelet coefficients and the amount of input data, but does not depend on the actual signal.

Whereas with traditional sharpening the problem of sharpening not only
10 “real” edges, but also noise pixels, occurs wavelet sharpening and denoising can be done, for example, by choosing a threshold, multiplying all coefficients above that threshold by $\mu_j = 2^{\alpha}$ and setting all coefficients below a threshold to zero. This leads to easy implementation of signal adaptive smoothing and sharpening as needed or required, e.g., in a digital copier.

15 A common model for noise in data is additive Gaussian White noise. A technique developed by Donoho and Johnstone for denoising with wavelets is a state of the art denoising technique. The denoising is performed by simply thresholding wavelet coefficients. The threshold depends only on the size of the data N , where N is the number of samples
20 (for an image, the number of samples is the number of pixels) and the standard deviation of the noise σ , the threshold is:

$$\sigma\sqrt{2\log N}$$

- The latter parameter can be estimated from the standard deviation of the first level of wavelet coefficients. Asymptotically, all noise should be removed as N goes to infinity using that technique. However, in practical application, there may still be some noise present in the data due to the finiteness of the data or different threshold selection. It is also known that the human visual system corresponds positively to some noise present in, for example, images. After the rescaling (sharpening or smoothing) of wavelet coefficients described herein, the inverse transform transforms the remaining White noise into Colored noise (e.g., coloring remaining noise).
- Similarly, the wavelet coefficients may have to be renormalized, particularly to maintain the proportions of modified wavelet coefficients and original scaling coefficients as described in more detail below. The renormalization may be performed by applying a scalar to the coefficients in all levels or a subset of all levels. In one embodiment, renormalization may be combined with the sharpening or smoothing by multiplying all coefficients at one or more of the decomposition levels by a scale dependent parameter chosen to achieve renormalization and sharpening/smoothing. In an alternative embodiment, renormalization may be performed by computing a range of wavelet coefficients (e.g., the minimum and maximum coefficient values) before rescaling, and then perform the rescaling (sharpening or smoothing). Thereafter, the complete set of modified coefficients are scaled back to the original range (e.g., mapping the

smoothed or sharpened coefficients back into the original range specified by the minimum and maximum coefficient values) before the rescaling.

Figure 2 illustrates another embodiment of the process for processing image data. The process is performed by processing logic that may

5 comprise hardware, software, or a combination of both. Referring to Figure 2, the process begins by processing logic decomposing the image data into multiple decomposition levels by applying a wavelet transform to the image data (processing block 201).

10 Once decomposition has been completed, then processing logic classifies the coefficients at different decomposition levels and bands (processing block 202). This classification is optional. In one embodiment, coefficients are classified into "text" and "background" depending on a predetermined criterion. The resulting classification may be used for adapting the smoothing or sharpening to compensate for the type of data
15 being processed.

Then, processing logic performs denoising on coefficients in one or more of the decomposition levels (processing logic 203).

After performing the decomposition and classification, the processing logic modifies in multiple decomposition levels by scaling classified
20 coefficients in those decomposition levels using different scale (level) dependent parameters for each of the decomposition levels (processing block 204). In one embodiment, the parameters may be band dependent parameters. For a 1D transform, there is one band (or subband) for each

scale (level). For 2D or higher dimensional transforms, each band is a particular scale (level) and orientation. For example, a two 2D transform has a band for the first scale (level) and for the vertical detail (high-pass) and the horizontal smooth (low-pass).

5 After sharpening or smoothing has been performed, processing logic performs renormalization on the coefficients (processing block 205) on all levels or a subset of all levels. Once renormalization has been performed, processing logic performs an inverse transform on scaled (and unscaled) coefficients (processing block 206).

10 Note that techniques for sharpening and smoothing described herein are advantageous in that “real” edges are magnified over various scales more than noise pixels and smooth areas are smoothed over various scales. The techniques may also outperform the traditional unsharp masking with respect to the quality of the processed image.

15 Sharpening/Smoothing Theory

 The theory behind the sharpening and smoothing techniques of the present invention, is described below. In the following, a description is given as to how these results can be used for deriving multiscale unsharp
20 masking via discrete wavelet decompositions.

 Let $\{H, H^*, G, G^*\}$ be a quadruple of biorthogonal wavelet filters (H = lowpass, G = highpass), where H and G are used in the forward transform

and H^* and G^* in the inverse transform. In the Z-transform domain a 2-channel perfect reconstruction filter bank is required to satisfy the following conditions (see e.g., G. Straug, T. Nguyen, "Wavelets and Filter Banks," Wellesley-Cambridge Press, 1996).

$$5 \quad H^*(z) H(z) + G^*(z) G(z) = 2 z^{-m} \quad (4)$$

$$H^*(z) H(-z) + G^*(z) G(-z) = 0. \quad (5)$$

As a consequence the following equality, also known as perfect reconstruction property, is guaranteed for an arbitrary signal X :

$$z^m X(z) = \frac{1}{2} [H^*(z)H(z)X(z) + H^*(z)H(-z)X(-z)] + \frac{1}{2} [G^*(z)G(z)X(z) + G^*(z)G(-z)X(-z)].$$

10 Introducing the following notations:

$$F_0[X](z) := \frac{1}{2} [H^*(z)H(z)X(z) + H^*(z)H(-z)X(-z)] \quad (\text{lowpass output}) \text{ and}$$

$$F_1[X](z) := \frac{1}{2} [G^*(z)G(z)X(z) + G^*(z)G(-z)X(-z)] \quad (\text{highpass output})$$

the perfect reconstruction property can be rewritten as

$$z^m X(z) = F_0[X](z) + F_1[X](z). \quad (6)$$

15 If the filters H and G are symmetric and centered around zero the delay is zero, i.e. $m=0$.

Since F_0 is a lowpass and F_1 is a highpass filter, there exists a wavelet formulation of the definition of a sharpened image $F_{\text{dwt-s}}(x)$ by

$$x_{\text{dwt-s}}[z] := F_0[x](z) + \mu F_1[x](z). \quad (7)$$

where the wavelet sharpening parameter μ is equivalent to the parameter λ in the traditional sharpening method in Eq(1).

When computing scaling and wavelet coefficients at larger decomposition levels, the input data X are the scaling coefficients s^j at a specific scale j . The wavelet sharpening parameter μ can differ from scale to scale (i.e., level to level). The results from the theory of smoothness spaces, which is described in, for example, Y. Meyer, "Wavelets and Operators," Cambridge University Press, Cambridge, WC, 1992, lead in a natural way to a definition of multiscale sharpening by choosing a scale-dependent sharpening parameter.

$$\mu_j = 2^{j\alpha}. \quad \text{with } \alpha < 0 \quad (8)$$

The parameter α changes the overall smoothness of the signal in terms of Hoelder regularity.

The "sharpened" scaling coefficients $s_{\text{dwt-s}}^j$ at scale j are then defined as

$$s_{\text{dwt-s}}^j = F_0[s^j] + \mu_j F_1[s^j]. \quad (9)$$

Analogous to the theoretical results on smoothness characterization, the parameter choice $\alpha < 0$ sharpens the image. The range of α is bounded by constraints given through the chosen wavelet system. A block diagram of a first stage of a filter bank implementation of this method is shown in Figure

3. Referring to Figure 3, an input signal X is input into a low pass (H) wavelet filter 301 and a high pass (G) filter 302. The outputs of filters 301 and 302 are coupled to decimation units 303 and 304, respectively, which decimate the signals from filters 301 and 302 by two (critically subsampled).

- 5 Line 305 represents the separation between the analysis portion and the synthesis portion of the system shown in Figure 3. Although not shown, the low pass transferred signals may be input into filters 301 and 302 iteratively to create additional decompositional levels with parameter m_j . This process may be repeated to create any number of decomposition levels (e.g.,
- 10 2, 3, 4, 5, etc.).

Between the analysis portion and the synthesis portion, a coder and decoder may be included (not shown to avoid obscuring the invention). The coder and decoder may contain all the processing logic and/or routines performed in the transformed domain (e.g., prediction, quantization, coding,

15 etc.).

The critically subsampled signals that are output from decimation unit 304 are input to scaling unit 306 (after any coding and decoding). Scaling unit 306 applies different scale dependent parameters μ to transformed signals of multiple decomposition levels.

The subsampled transformed signals that are output from decimation unit 303 and the scaled output from scaling unit 306 are input to upsampling units 307 and 308, respectively, which upsamples the transformed signals by 2 (e.g., a zero is inserted after every term) and then passes the signals to low pass inverse wavelet transform filter 309 and high pass inverse wavelet transform filter 310, respectively. The outputs of filters 309 and 310 are combined by addition unit 311 to produce an output signal X^1 . Addition unit 311 adds its two inputs. In alternative embodiments, addition unit 311 may write to alternating locations in memory (e.g., frame buffer) or store the information using addresses selected to result in the combined output.

In order to preserve the total energy of the image and to maintain the proportions of modified wavelet and original scaling coefficients a renormalization of wavelet coefficients may be used. In one embodiment, this is done by dividing the modified coefficients by $\sqrt{n_{\alpha\gamma}}$ where

$$n_{\alpha,\gamma} = \left[\frac{2^{(L+1)2(\gamma+\alpha)} - 2^{2(\gamma+\alpha)}}{2^{2(\gamma+\alpha)} - 1} \right] / \frac{2^{(L+1)2\gamma} - 2^{2\gamma}}{2^{2\gamma} - 1} \text{ for } -\alpha \neq \gamma. \quad (10)$$

$$n_{\alpha,\gamma} = L \left\lceil \frac{2^{(L+1)2\gamma} - 2^{2\gamma}}{2^{2\gamma} - 1} \right\rceil \text{ for } -\alpha = \gamma. \quad (11)$$

γ is the upper bound on the Hoelder regularity range of the wavelet system and α is the chosen sharpening parameter. For a Daubechies-8 wavelet system of order 4 (filter length = 8, $\gamma = 1.596$ with $\alpha = -1.596$ the

5 normalization factor results in

$$\sqrt{L \left\lceil \frac{2^{(L+1)-3.192} - 2^{3.192}}{2^{3.192} - 1} \right\rceil}. \quad (12)$$

Hoelder regularity and vanishing moments for various Daubechies wavelet systems from the book by Ingrid Daubechies, "Ten Lectures on Wavelets,"

10 SIAM, Philadelphia, PA, 1992 are shown in Table 1 below:

Table 1

Daubechies wavelet system of order N	Hoelder regularity	Vanishing moments	γ =min(Hoelder, vanishing moments)
1	-	1	-
2	≥ 0.5	2	≥ 0.5
3	≥ 0.915	3	≥ 0.915
4	≥ 1.596	4	≥ 1.596
5	≥ 1.888	5	≥ 1.888
6	≥ 2.158	6	≥ 2.158

The parameter γ is the minimum of vanishing moments and Hoelder regularity. Alternative renormalization techniques may be used.

The lack of shift-invariance of the critically sampled DWT is a disadvantage for image processing steps such as denoising and also

5 multiscale smoothing and sharpening because one particular edge could be smoothed or sharpened differently depending on the alignment of the edge in the wavelet tree. To overcome this disadvantage, an overcomplete (redundant) DWT, denoted by RDWT, is chosen and outperforms the critically sampled DWT. If an RDWT is chosen for sharpening an image, the

10 same approach as described above may be used to define a multiscale unsharp masking. The main difference is that down- and up-sampling steps in the filter bank are neglected.

The perfect reconstruction property of the RDWT at scale 1 is given by

15
$$x(z) = \frac{1}{2} (H^* H[x](z) + G^* G[x](z)). \quad (13)$$

A schematic overview is shown in Figure 4. Referring to Figure 4, an input signal X is input to low pass wavelet transform filter 401 and high pass wavelet transform filter 402. The output of filter 401 is separated into even coefficients 403 and odd coefficients 404, and the output of filter 402 is

separated into even coefficients 405 and odd coefficients 406. Note that no decimation is performed. As with line 305 of Figure 3, line 407 again represents the separation between the analysis and synthesis portions and may include coding and decoding operations as described herein. Also, the

5 coefficients output from low pass filter 401 may be fed back into filters 401 and 402 iteratively to create a number of decomposition levels.

Scaling units 408 and 409 apply a scale dependent parameter to the even and odd coefficients as described above to multiple decomposition levels. The outputs of scaling units 408 and 409 and the even and odd

10 coefficients from filter 401 are upsampled by upsampling units 410-413. The outputs of upsampling units 410 and 411 are coupled to inputs of low pass inverse transform filters 414 and 415 respectively, and the outputs of upsampling units 412 and 413 are coupled to inputs of high pass inverse transform filters 416 and 417 respectively. The outputs of inverse filters 414-

15 417 are coupled to divider units 418-421, which divide the outputs by 2 to results in averaging two numbers to compensate for the use of an overcomplete DWT. The renormalization proceeds along the same lines as for a DWT, just the value gamma for the wavelet system is, roughly speaking, doubled (see table).

Addition unit 422 adds the outputs of decoder units 418 and 419, while addition unit 423 adds the outputs of divider units 420 and 421. Addition unit 424 adds the outputs of addition units 422 and 423 to create the X^1 signal. Addition units 422-424 may operate in a well-known manner, such as, for example, described above.

If the filters H and G are orthogonal the filters H^*H and G^*G in the first stage of the filter bank are simply the autocorrelation filters of H and G .

For scales $j > 1$ the perfect reconstruction property is expressed using not the original filters H, H^*, G, G^* , but iterated versions of those, denoted by

H_j, H_j^*, G_j, G_j^* , as follows:

$$s^{j-1}(z) = \frac{1}{2} (H_j^* H_j [s^{j-1}](z) + G_j^* G_j [s^{j-1}](z)).$$

In analogy with the critically sampled case, a sharpened image x_{rdwt-s} can be defined as

$$x_{rdwt-s} := \frac{1}{2} (H^* H [x] + \mu G^* G [x]). \quad (14)$$

By choosing $\mu^j = 2^{j\alpha}$ sharpened ($\alpha < 0$) late scaling coefficients may be obtained by

$$S_{rdwt-s}^1 = \frac{1}{2} (H^* H [S^1] + \mu_1 G^* G [S^1]). \quad (15)$$

at scale $j=1$. For scales $j>1$ the sharpened scaling coefficients are defined as

$$S'_{rdwt-s} = 1/(2^{j+1}) (H_j^* H_j [S'] + \mu_j G_j^* G_j [S']). \quad (16)$$

The filter bank implementation for overcomplete multiscale sharpening is shown in Figure 4. Compared to the maximal decimated filter bank structure in Figure 3, the down-sampling by a factor of two is neglected. But in the same way as in Figure 3, the detail coefficients are multiplied by μ_j . In contrast to the critically sampled DWT, the range of possible exponents is extended.

The normalization of modified wavelet coefficients may be performed in the same way as for the critically sampled DWT. The renormalization proceeds along the same lines as for a DWT, except that the value σ for the wavelet system is, roughly speaking, doubled. For overcomplete transforms, the values change as shown in Table 2 below:

Table 2

Daubechies wavelet system of order N	Hoelder regularity of overcomplete system	Vanishing moments of overcomplete systems	γ =min(Hoelder, vanishing moments)
1	≥ 1	2	1
2	≥ 1.0	4	1.0
3	≥ 1.830	6	1.830
4	≥ 3.192	8	3.192
5	≥ 3.776	10	3.776
6	≥ 4.316	12	4.316

Similarly to multiscale sharpening for critically sampled and overcomplete wavelet transforms, multiscale smoothing is possible for critically sampled and overcomplete wavelet transforms by choosing the parameter α to be greater than zero.

There are some advantages of knowing the smoothness of the original data and the processed input data. Assume the input data is a smoothing of the original data by rescaling wavelet coefficients obtained from applying an orthogonal DWT, then the technique described herein can reconstruct the original data exactly. For example, it means that a smoothed step edge in the processed input data can be reversed to the original step edge.

Multiscale smoothing and sharpening using a DWT with orthogonal wavelets is invertible, while, in contrast, the RDWT is not invertible. The reason for this is that the RDWT is not an orthogonal transform and, in general,

$$\frac{1}{2} H (H^* H[x] + \mu G^* G[x]) + \frac{1}{2} G (H^* H[x] + \mu G^* G[x]) \neq H[x] + \mu G[x]. \quad (17)$$

Figure 5 illustrates a flow chart of one embodiment of the process for performing multi-scale sharpening and smoothing with wavelets. Referring to Figure 5, the process begins with processing logic receiving input

parameters (processing block 501). In one embodiment, the input parameters comprise the type of wavelet system, the number of decomposition levels, the sharpening/smoothing parameter, and the denoising technique. With respect to the denoising technique, the input

5 parameters comprise thresholds for the denoising technique.

Once the input parameters have been received, processing logic looks up the smoothness value γ for the chosen wavelet system (processing block 502) and computes the renormalization factor are using the formula given above (processing block 503). The values of γ may be stored in a look up

10 table, with each entry being associated with a different wavelet system. The processing blocks 501-503 represent an initialization portion of the process. These steps are performed once, with the remaining steps being performed for every image.

After initialization, processing logic performs a first level wavelet

15 transform (processing block 504). Processing logic then sets the threshold for denoising (processing block 505). In one embodiment, if the Donoho - Johnstone threshold is used for denoising, processing logic computes the standard deviation of wavelet coefficients and sets the threshold to:

$$\sigma \sqrt{2 \log N}$$

where N is the maximum of the rows and columns of the data and σ is the standard deviation of the first level of wavelet coefficients.

Next, processing logic performs the second level wavelet transform on the coefficients (processing block 507₂). Processing logic performs other
 5 wavelet transforms up to the L -th level of the wavelet transform (processing block 507 _{L}).

After performing the wavelet transforms, processing logic performs thresholding (denoising) and rescaling (sharpening or smoothing) by multiplying wavelet coefficients at level j with:

$$10 \quad 2^{j\alpha}$$

(processing block 508). Thereafter, processing logic performs L levels of the inverse transform (processing block 509).

Figures 6A-D illustrate forward and inverse transform. Figure 6A and B illustrate building blocks for the forward and inverse discrete wavelet
 15 transform (DWT) respectively. Note that these are similar to the similarly named blocks in Figure 3. Figure 6C is one embodiment of a forward DWT for L levels of decomposition. Referring to Figure 6C, the input X is input into the level one forward DWT block 601. The output of the level one forward DWT 601 is input to the level two forward DWT block 602 and

continues through the remaining levels of decomposition to level L in similar fashion. Figure 6D illustrates the inverse DWT with rescaling (sharpening/smoothing) L levels of decomposition. Referring to Figure 6D, noted that there is a sharpening/smoothing parameter for each level of the

5 inverse DWTs. That is, the sharpening/smoothing parameter is the same for all transform steps being performed on the same level.

Figures 7A-D illustrate the application of sharpening/smoothing to RDWTs. Figures 7A-7B illustrate the building block for forward and inverse redundant DWT (RDWT), respectively. Figure 7C illustrates a forward

10 RDWT for L levels of decomposition. Figure 7D illustrates the inverse RDWT for all levels of decomposition with rescaling (sharpening/smoothing) for L levels of decomposition. Referring to Figure 7D, the rescaling parameter is the same for each of the individual processing blocks in each level. However, the rescaling parameter may be different

15 from level to level.

Selecting the Sharpening/Smoothing Parameter

Depending on knowledge about the smoothness of the input data and output data, there are different possibilities to determine the parameter α .

Four different techniques are described below; however, other techniques may be used. First, if the available input data are data obtained from sending original data through an input device, such as a scanner, the Hoelder regularity of the data is that of the input device. In case of the

5 scanner, the regularity is given by the smoothness of the pointspread function. If the original data have smoothness β and the scanned input data have smoothness ϵ , then a reasonable choice for the sharpening parameter would be $-(\epsilon - \beta)$. However, the term $|\epsilon - \beta|$ is not allowed to be larger than γ , the Hoelder regularity of the wavelet system. Therefore, the sharpening

10 parameter should be $\alpha = 0$ if $\beta > \gamma$ and $\epsilon > \gamma$, and $\alpha = \min(\gamma, \epsilon) - \beta$ if $\beta \leq \gamma$.

If the knowledge of the smoothness of the input data does not exist, the corresponding Hoelder regularity ϵ can be estimated from the decay of wavelet coefficients across scale. The Hoelder regularity ϵ should be the smallest number such that

15
$$\left| d_{j,k} \right| \leq C 2^{j\left(\frac{\epsilon+1}{2}\right)}$$
 for a constant $C > 0$ and scales j and positions k .

If the original data contain step edges as occurs, in the text regions, for example the original smoothness β is equal to zero.

Given the smoothness β of the original data the sharpening/smoothing parameter α should be always chosen such that that $0 \leq \beta + \alpha \leq \gamma$.

When processing a scanned image, the exponent $\alpha = -1$ may be used, which has a theoretical reason. An image can be modeled as a function that consists of smooth regions and step edges. By scanning this image, the step edges get blurred. This blurring can be modeled as a convolution with a Gaussian kernel or a kernel of similar characteristic. As a consequence, the overcomplete wavelet decomposition with the Haar system will capture a decay of wavelet coefficients described by the exponent 1. In order to sharpen the scanned image, i.e. to reverse smoothing of the edges, the exponent $\alpha = -1$ is chosen as an exponent in the sharpening parameter. The parameter γ in the normalization constant in Eq.(10) above is $\gamma = 1$. In this case for a total decomposition level $L=3$, the following modifications of the wavelet coefficients have to be made:

- multiplication of the first level of wavelet coefficients by $(2^{-1})/\sqrt{9/(2^8 - 4)} = 2.6458$
- multiplication of the second level of wavelet coefficients by $(2^{-2})/\sqrt{9/(2^8 - 4)} = 1.3229$
- multiplication of the third level of wavelet coefficients by $(2^{-3})/\sqrt{9/(2^8 - 4)} = 0.6614$

Thus, a general scheme has been described of how to choose the sharpening parameter in applications that involve scanned documents, e.g., in a digital copier, a digital camera, facsimile machine, printer, etc.

Another application of the multiscale sharpening and smoothing is to perform an adaptive smoothing or sharpening depending on the wavelet coefficients. Therefore, that only selected coefficients get sharpened by multiplication with 2^α with $\alpha < 0$ and coefficients in smooth areas get smoothed by multiplication by 2^β with $\beta > 0$ with a overcomplete Haar system.

One embodiment of a digital copier is shown in Figure 8. Referring to Figure 8, a scanner 801 or other halftone image source 802 supplies an image to classifier unit 803, which classifies the image data as text and background. The output of classifier unit 803 is received by scaling unit 804 which performs smoothing or sharpening depending on the classified pixel. Note that the use of classification and basing the sharpening/smoothing on the classification is optional. The output of scaling unit 804 is coupled to processing unit 805 which performs other processes (e.g., downsampling, gamma correction, halftone, etc.). The output of processing unit 805 is received by printer 806, which prints the image.

Whereas many alterations and modifications of the present invention will no doubt become apparent to a person of ordinary skill in the art after having read the foregoing description, it is to be understood that any particular embodiment shown and described by way of illustration is in no way intended to be considered limiting. Therefore, references to details of various embodiments are not intended to limit the scope of the claims which in themselves recite only those features regarded as essential to the invention.

10

Thus, a method and apparatus for performing data processing has been described.

CLAIMS

I claim:

- 1 1. A method comprising:
2 receiving input data; and
3 performing multi-scale unsharp masking on the input data.

- 1 2. A method for processing input data comprising:
2 decomposing the input data into a plurality of decomposition levels
3 by applying a wavelet transform to the input data; and
4 modifying coefficients in at least two of the plurality of
5 decomposition levels by scaling coefficients in the at least two
6 decomposition levels using different scale dependent parameters for each of
7 the decomposition levels.

- 1 3. The method defined in Claim 2 wherein the input data
2 comprises image data.

- 1 4. The method defined in Claim 2 wherein only wavelet
2 coefficients are scaled.

- 1 5. The method defined in Claim 2 wherein modifying coefficients
2 comprises multiplying each coefficient in one of the decomposition levels by

3 a first scale dependent parameter and multiplying each coefficient in another
4 of the decomposition levels by a second scale dependent parameter

1 6. The method defined in Claim 2 wherein each of the different
2 scale dependent parameters is determined according to the following
3 formula:

$$4 \mu_j = 2^{j\alpha}$$

5 where the value of α indicates whether sharpening or smoothing is applied
6 to coefficients and j indicates the scale.

1 7. The method defined in Claim 6 wherein sharpening is applied
2 to coefficients if α is less than zero and smoothing is applied to coefficients if
3 α is greater than zero.

1 8. The method defined in Claim 2 wherein modifying coefficients
2 results in smoothing of coefficients for scale dependent parameters greater
3 than a transition value and results in sharpening of coefficients for scale
4 dependent parameters less than the threshold value.

1 9. The method defined in Claim 8 wherein the transition value is
2 1.

- 1 10. The method defined in Claim 2 wherein the transform
2 comprises a critically sampled discrete wavelet transform.
- 1 11. The method defined in Claim 2 wherein the transform
2 comprises an overcomplete discrete wavelet transform.
- 1 12. The method defined in Claim 2 wherein the transform
2 comprises a complex wavelet transform.
- 1 13. The method defined in Claim 2 wherein the transform
2 comprises a critically sampled wavelet packet transform.
- 1 14. The method defined in Claim 2 wherein the transform
2 comprises an overcomplete wavelet packet transform.
- 1 15. The method defined in Claim 2 wherein decomposing the
2 image data comprises applying a transform to the input data wherein the
3 transform comprises an overcomplete transform for selected subbands.
- 1 16. The method defined in Claim 2 further comprising selecting
2 the scale dependent parameter based on knowledge of the input data and
3 knowledge of the image source.

1 17. The method defined in Claim 16 wherein the knowledge of the
2 image source comprises a model point spread function of the image source.

1 18. The method defined in Claim 16 wherein the knowledge of the
2 data comprises an indication the data contains step edges.

1 19. The method defined in claim 16 wherein selecting the scale
2 dependent parameter is based on an estimate of decay of wavelet
3 coefficients across scales.

1 20. The method defined in Claim 2 further comprising performing
2 an inverse transform on coefficients after scaling has been performed.

1 21. The method defined in Claim 2 further comprising denoising
2 after applying the wavelet transform.

1 22. The method defined in Claim 21 further comprising
2 performing denoising as part of scaling coefficients by multiplying all
3 coefficients in one of the decomposition levels above a predetermined
4 threshold and setting other coefficients to a value near zero.

1 23. The method defined in Claim 22 wherein the value is zero.

1 24. The method defined in Claim 24 further comprising
2 performing denoising as part of scaling coefficients by reducing all
3 coefficients by a predetermined amount to a value near zero and then
4 multiplying all coefficients in one of the decomposition levels above a
5 predetermined threshold and reducing all coefficients by a predetermined
6 amount to a value near zero.

1 25. The method defined in Claim 24 wherein the value is zero.

1 26. The method defined in Claim 21 further comprises coloring
2 noise that remains after scaling coefficients.

1 27. The method defined in Claim 2 wherein the different scale
2 dependent parameters are based on desired smoothness and sharpness.

1 28. The method defined in Claim 2 further comprising
2 renormalizing coefficients.

1 29. The method defined in Claim 28 wherein renormalizing
2 coefficients comprises applying a scalar to coefficients in at least one
3 decomposition level.

1 30. The method defined in Claim 28 wherein renormalizing
2 coefficients is performed as part of scaling coefficients by multiplying all
3 coefficients in one of the decomposition levels by a scale dependent
4 parameter chosen to achieve renormalization.

1 31. The method defined in Claim 28 wherein renormalizing
2 coefficients is performed as part of scaling coefficients by computing a range
3 of wavelet coefficients before rescaling, performing rescaling, and then
4 scaling modified coefficients back to the range before rescaling.

1 32. The method defined in Claim 2 wherein the scale dependent
2 parameters comprise monotonic functions.

1 33. The method defined in Claim 2 further comprising classifying
2 wavelet coefficients into types.

1 34. The method defined in Claim 33 wherein the types comprise
2 text and background.

1 35. A method for processing input data comprising:
2 decomposing the input data into a plurality of decomposition levels
3 by applying a wavelet transform to the input data;

4 performing denoising on coefficients in at least one of the plurality of
 5 decomposition levels;
 6 modifying coefficients in at least two of the plurality of
 7 decomposition levels by scaling coefficients in at least two decomposition
 8 levels using different scale dependent parameters for each of the
 9 decomposition levels;
 10 performing renormalization on coefficients;
 11 inverse transforming the coefficients.

1 36. The method defined in Claim 35 wherein the input data
 2 comprises image data.

1 37. The method defined in Claim 35 wherein modifying
 2 coefficients comprises multiplying each coefficient in one of the
 3 decomposition levels by a first scale dependent parameter and multiplying
 4 each coefficient in another of the decomposition levels by a second scale
 5 dependent parameter.

1 38. The method defined in Claim 36 wherein each of the different
 2 scale dependent parameters is determined according to the following
 3 formula:

4
$$\mu_j = 2^{j\alpha}$$

5 where the value of α indicates whether sharpening or smoothing is applied
6 to coefficients and j indicates the particular scale.

1 39. The method defined in Claim 38 wherein sharpening is applied
2 to coefficients if α is less than zero and smoothing is applied to coefficients if
3 α is greater than zero.

1 40. The method defined in Claim 35 wherein modifying
2 coefficients results in smoothing of coefficients for scale dependent
3 parameters greater than a transition value and results in sharpening of
4 coefficients for scale dependent parameters less than the threshold value.

1 41. The method defined in Claim 40 wherein the transition value is
2 1.

1 42. The method defined in Claim 35 further comprising
2 performing simultaneously denoising and sharpening by multiplying all
3 coefficients in one of the decomposition levels above a predetermined
4 threshold and setting other coefficients to a value near zero.

1 43. The method defined in Claim 42 wherein the value is zero.

1 44. The method defined in Claim 35 further comprising
2 performing denoising as part of scaling coefficients by reducing all
3 coefficients by a predetermined amount to a value near zero and then
4 multiplying all coefficients in one of the decomposition levels above a
5 predetermined threshold and reducing all coefficients by a predetermined
6 amount to a value near zero.

1 45. The method defined in Claim 44 wherein the value is zero.

1 46. The method defined in Claim 35 further comprising coloring
2 noise that remains after scaling coefficients.

1 47. The method defined in Claim 35 further comprising
2 renormalizing coefficients by applying a scalar to coefficients in at least one
3 decomposition level.

1 48. The method defined in Claim 47 wherein renormalizing
2 coefficients is performed as part of scaling coefficients by multiplying
3 coefficients in one of the decomposition levels by a scale dependent
4 parameter chosen to achieve renormalization.

1 49. A method for processing input data comprising:

2 decomposing the input data into a plurality of decomposition levels
3 by applying a wavelet transform to the input data; and
4 magnifying edges more than noise coefficients by multiplying
5 coefficients in different decomposition levels with different scale dependent
6 parameters.

1 50. A method for processing input data comprising:
2 decomposing the input data into a plurality of decomposition levels
3 by applying a wavelet transform to the input data; and
4 smoothing selected coefficients more than non-selected coefficients by
5 multiplying well in different decomposition levels with different scale
6 dependent parameters.

1 51. The method defined in Claim 50 wherein the selected
2 coefficients comprise background coefficients.

1 52. The method defined in Claim 50 wherein the selected
2 coefficients comprises constant regions

1 53. An apparatus for processing input data comprising:
2 means for decomposing the input data into a plurality of
3 decomposition levels by applying a wavelet transform to the input data; and

4 means for modifying coefficients in at least two of the plurality of
 5 decomposition levels by scaling coefficients in the at least two
 6 decomposition levels using different scale dependent parameters for each of
 7 the decomposition levels.

1 54. The apparatus defined in Claim 53 wherein the input data
 2 comprises image data.

1 55. The apparatus defined in Claim 53 wherein the means for
 2 modifying coefficients comprises means for multiplying each coefficient in
 3 one of the decomposition levels by a first scale dependent parameter and
 4 means for multiplying each coefficient in another of the decomposition
 5 levels by a second scale dependent parameter

1 56. The apparatus defined in Claim 53 wherein each of the
 2 different scale dependent parameters is determined according to the
 3 following formula:

$$4 \quad \mu_j = 2^{j\alpha}$$

5 where the value of α indicates whether sharpening or smoothing is applied
 6 to coefficients, and j indicates a particular scale.

1 57. The apparatus defined in Claim 56 wherein means for
2 modifying applies sharpening to coefficients if α is less than zero and applies
3 smoothing to coefficients if α is greater than zero.

1 58. The apparatus defined in Claim 53 wherein modifying
2 coefficients results in smoothing of coefficients for scale dependent
3 parameters greater than a transition value and results in sharpening of
4 coefficients for scale dependent parameters less than the threshold value.

1 59. The apparatus defined in Claim 58 wherein the transition
2 value is 1.

1 60. The apparatus defined in Claim 53 further comprising means
2 for performing an inverse transform on coefficients after scaling has been
3 performed.

1 61. The apparatus defined in Claim 53 further comprising means
2 for denoising after applying the wavelet transform.

1 62. The apparatus defined in Claim 53 further comprising means
2 for performing denoising as part of scaling coefficients by multiplying all
3 coefficients in one of the decomposition levels above a predetermined
4 threshold and setting other coefficients to a value near zero.

1 63. The apparatus defined in Claim 62 wherein the value is zero.

1 64. The apparatus defined in Claim 53 further comprising
2 performing denoising as part of scaling coefficients by reducing all
3 coefficients by a predetermined amount to a value near zero and then
4 multiplying all coefficients in one of the decomposition levels above a
5 predetermined threshold and reducing all coefficients by a predetermined
6 amount to a value near zero.

1 65. The apparatus defined in Claim 64 wherein the value is zero.

1 66. The apparatus defined in Claim 53 further comprising means
2 for renormalizing coefficients.

1 67. The apparatus defined in Claim 66 wherein the means for
2 renormalizing coefficients comprises means for applying a scalar to
3 coefficients in at least one decomposition level.

1 68. The apparatus defined in Claim 66 wherein the means for
2 renormalizing coefficients operates as part of scaling coefficients by
3 multiplying all coefficients in one of the decomposition levels by a scale
4 dependent parameter chosen to achieve renormalization.

1 72. The article of manufacture defined in Claim 71 wherein
2 sharpening is applied to coefficients if α is less than zero and smoothing is
3 applied to coefficients if α is greater than zero.

1 73. The article of manufacture defined in Claim 69 wherein
2 modifying coefficients results in smoothing of coefficients for scale
3 dependent parameters greater than a transition value and results in
4 sharpening of coefficients for scale dependent parameters less than the
5 threshold value.

1 74. The article of manufacture defined in Claim 73 wherein the
2 transition value is 1.

1 75. An apparatus for processing input data comprising:
2 a forward wavelet filter to convert the input data into coefficients in a
3 plurality of decomposition levels;
4 a scaling unit to modifying coefficients in at least two of the plurality
5 of decomposition levels by scaling coefficients in the at least two
6 decomposition levels using different scale dependent parameters for each of
7 the decomposition levels; and
8 an inverse wavelet filter coupled to the scaling unit.

1 82. The apparatus defined in Claim 80 wherein the transition
2 value is 1.

1 82. A copier comprising:
2 an image source;
3 a classifier unit coupled to the image source;
4 a scaling unit coupled to the classifier unit comprising
5 a forward wavelet filter to convert the image data into
6 coefficients in a plurality of decomposition levels,
7 a scaling unit to modifying coefficients in at least two of the
8 plurality of decomposition levels by scaling coefficients in the at least
9 two decomposition levels using different scale dependent parameters
10 for each of the decomposition levels,
11 an inverse wavelet filter coupled to the scaling unit; and
12 a printer coupled to the scaling unit.

1 83. The copier defined in Claim 82 wherein the scaling unit
2 multiplies each coefficient in one of the decomposition levels by a first scale
3 dependent parameter and multiplies each coefficient in another of the
4 decomposition levels by a second scale dependent parameter

ABSTRACT OF THE DISCLOSURE

A method and apparatus for processing image data are described. In one embodiment, a method of processing image data comprises decomposing the image data into multiple decomposition levels by applying a wavelet transform to the image data, and modifying coefficients in at least two of the decomposition levels by scaling coefficients in theses decomposition levels using different scale dependent parameters for each of the decomposition levels.

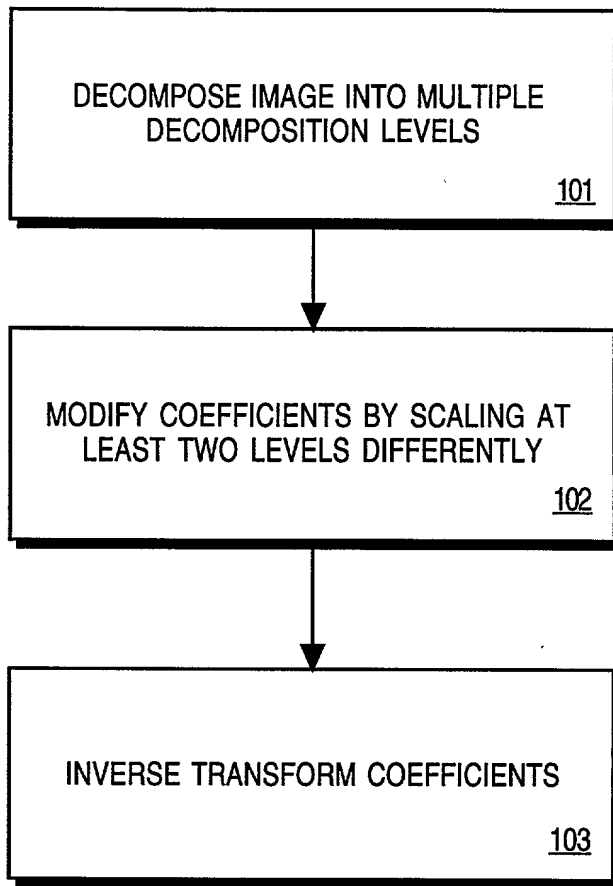


FIG. 1

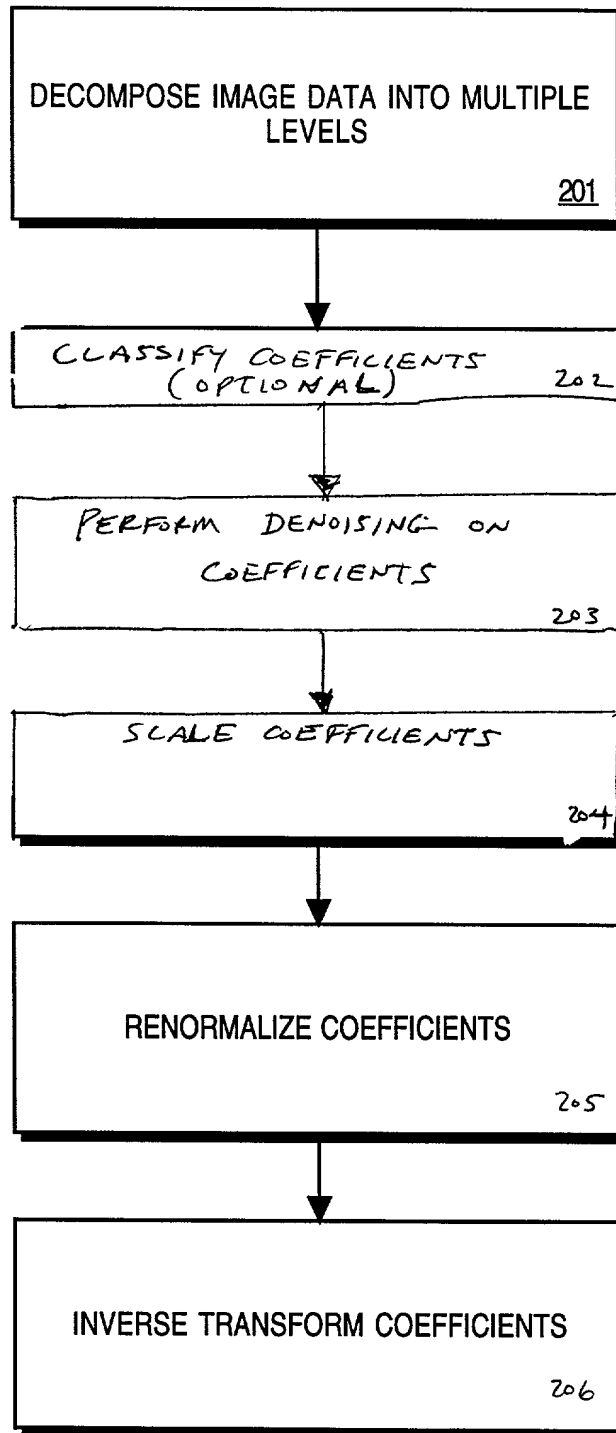


FIG. 2

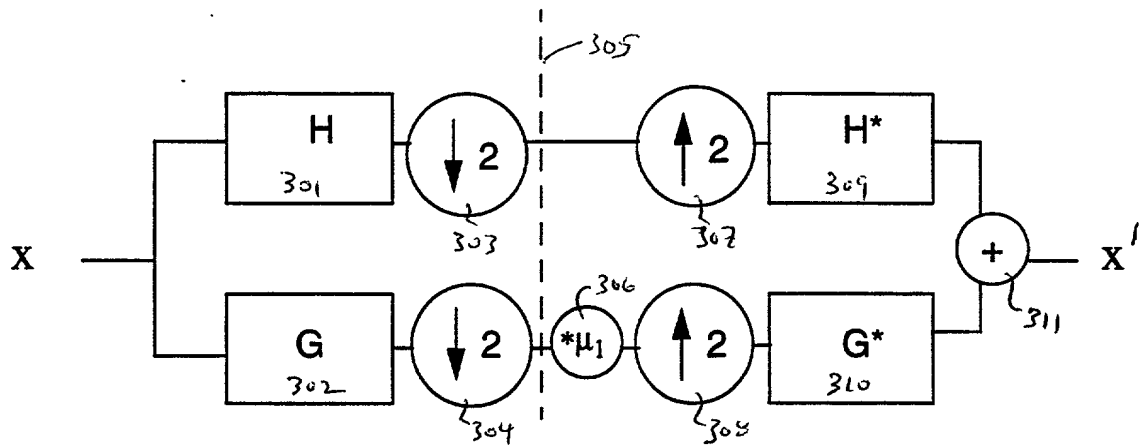


Figure 3

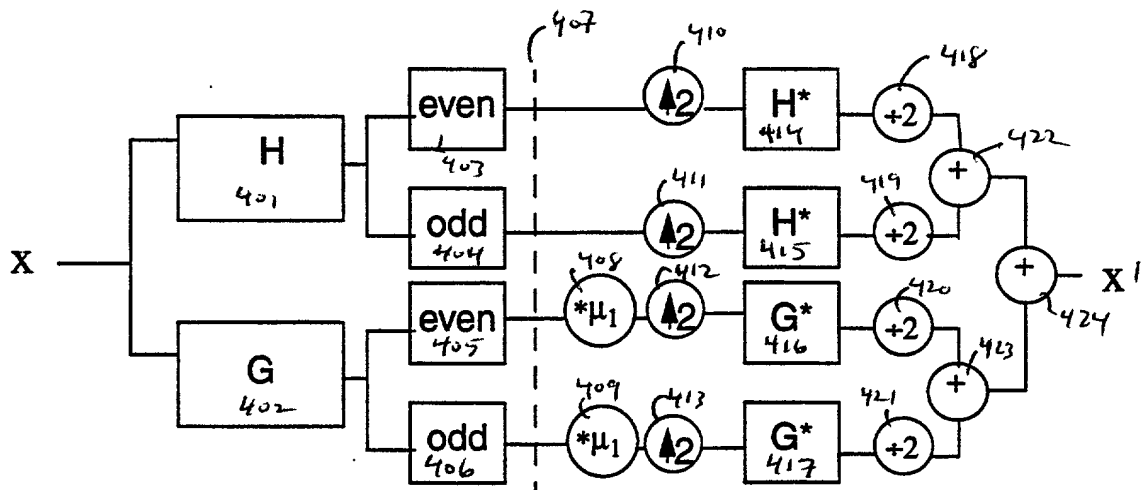


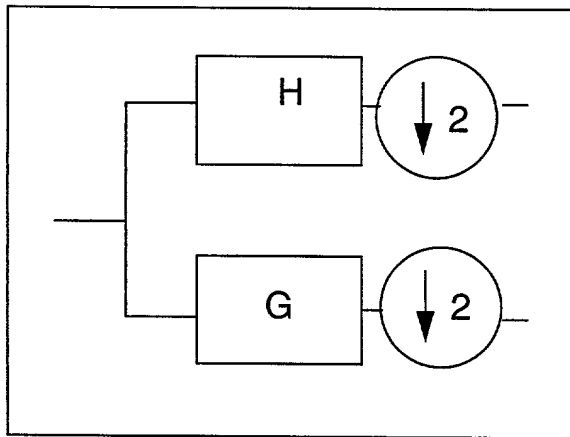
Figure 4

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graph TD
    501[Input parameters: wavelet system, level L of decomposition, sharpening/smoothing parameter  $\alpha$ , denoising technique (thresholds)] --> 502[Lookup smoothness value  $\gamma$  for chosen wavelet system]
    502 --> 503[Compute renormalization factor R]
    503 --> 504[1st level wavelet transform]
    504 --> 506["If Donoho-Johnstone threshold is used for denoising compute standard deviation of wavelet coefficients  $\sigma$  and set threshold to  $\sigma\sqrt{2\log N}$  where N is the maximum of the size of rows and columns of the input data."]
    506 --> 507_1[2nd level wavelet transform]
    507_1 --> 507_2[...]
    507_2 --> 507_L[L-th level wavelet transform]
    507_L --> 508[Perform thresholding (denoising) and rescaling (sharpening or smoothing) by multiplying wavelet coefficients at level j with  $2^{j\alpha}/R$ ]
    508 --> 509[L levels inverse transform]

```

FIGURE 5



=

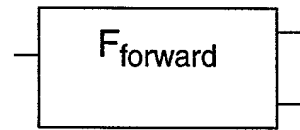
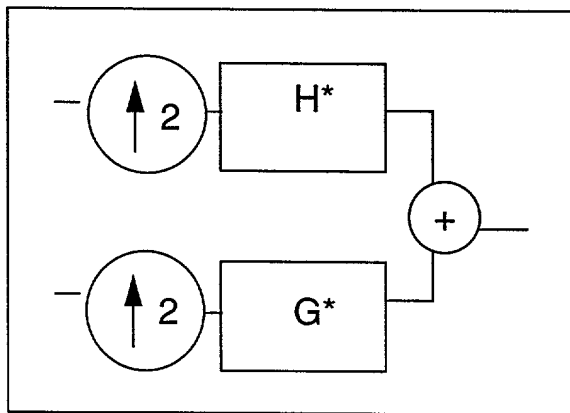


FIGURE 6A



=

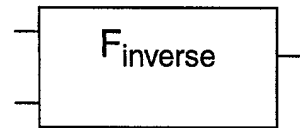


FIGURE 6B

level 1

level 2

level L

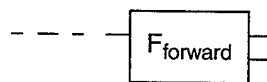
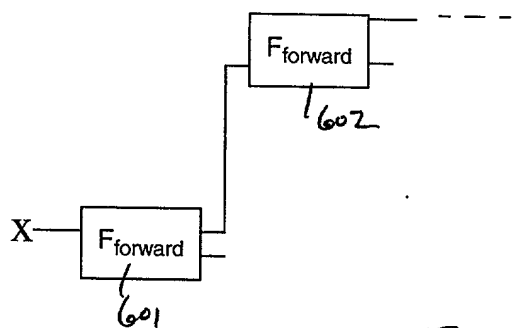


FIGURE 6C

level 1

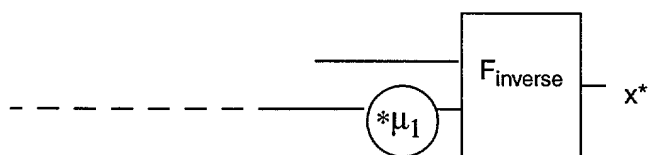
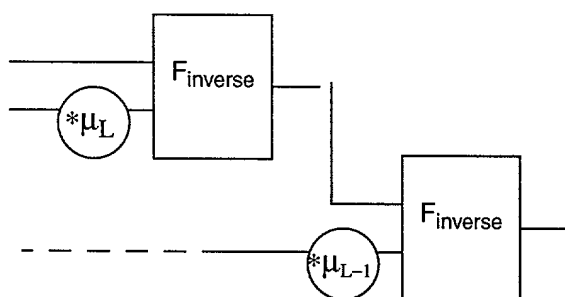


FIGURE 6D

40	My "New World"
41	My "New World"
42	My "New World"
43	My "New World"
44	My "New World"
45	My "New World"
46	My "New World"
47	My "New World"
48	My "New World"
49	My "New World"
50	My "New World"
51	My "New World"
52	My "New World"
53	My "New World"
54	My "New World"
55	My "New World"
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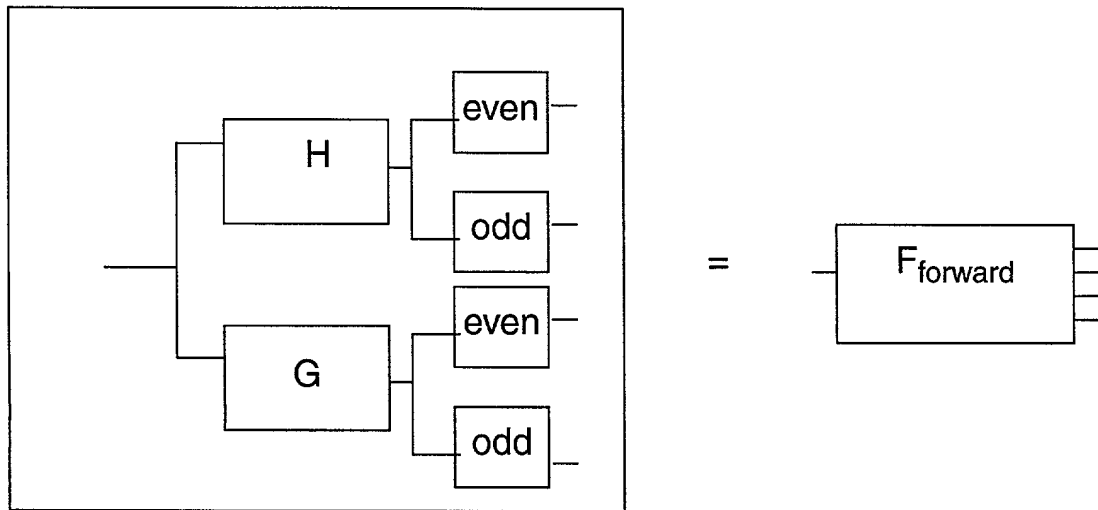


FIGURE 7A

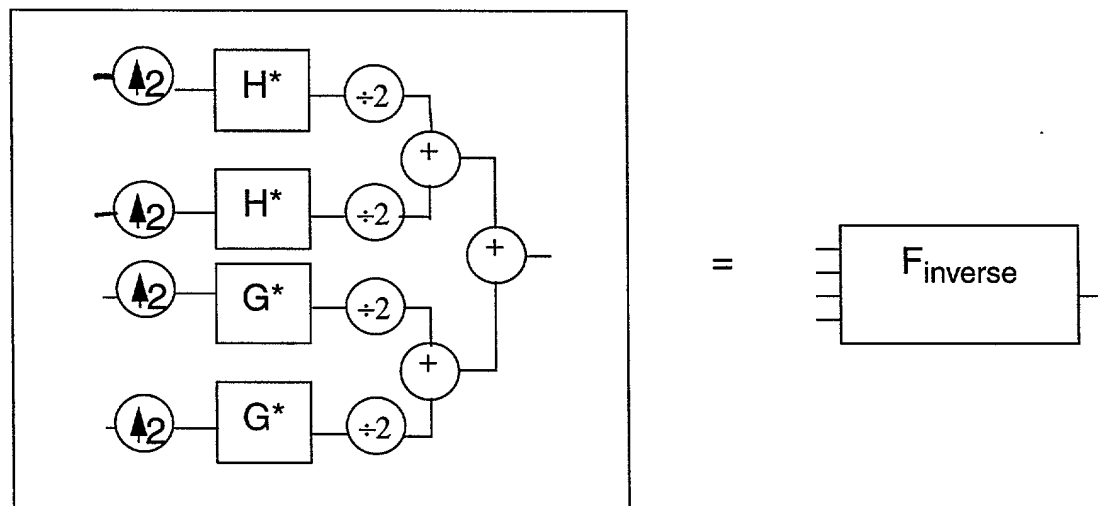


FIGURE 7B

1	name	type
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13	name	type
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100	name	type

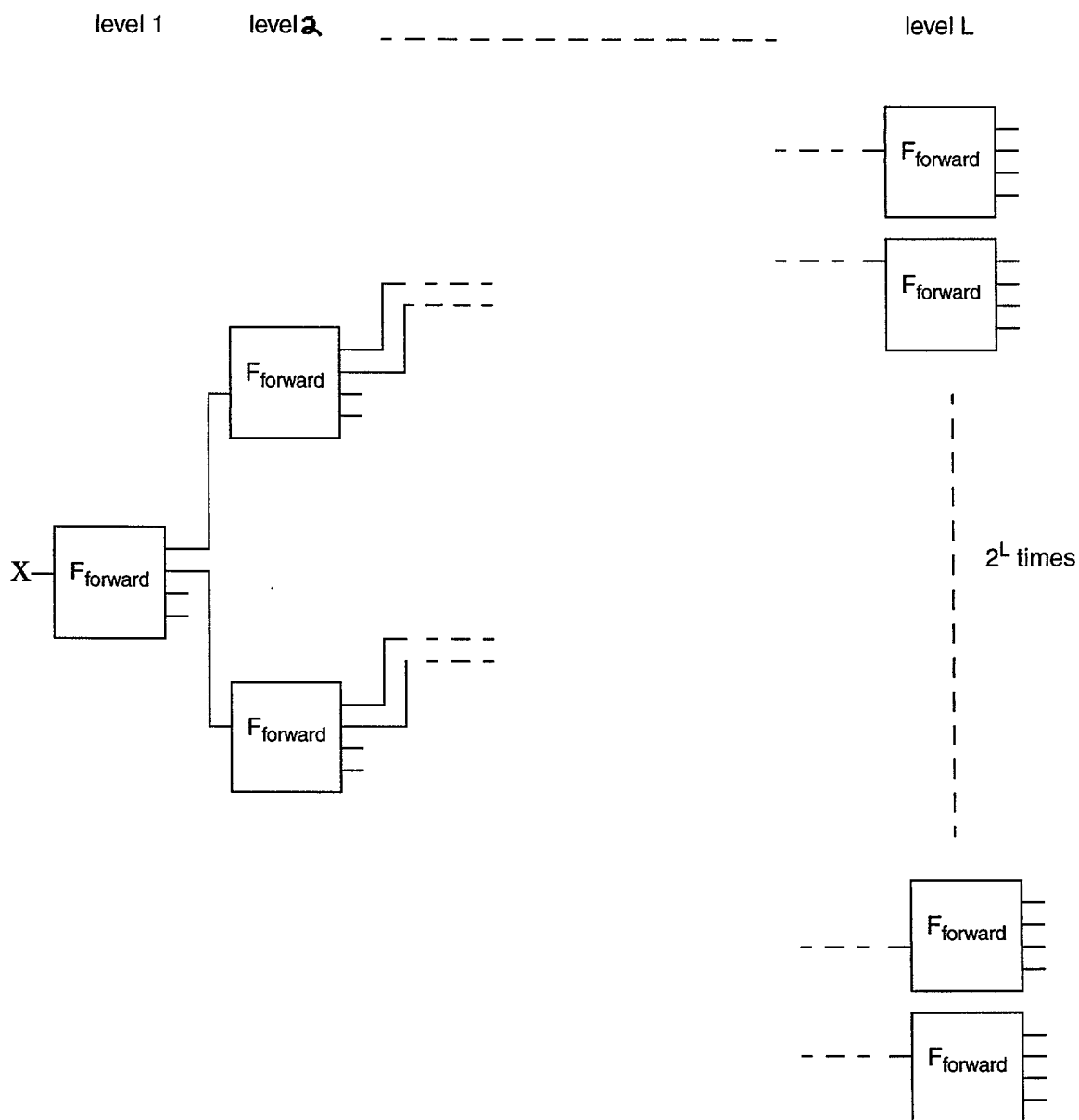


FIGURE 7C

level L

level L-1

level 1

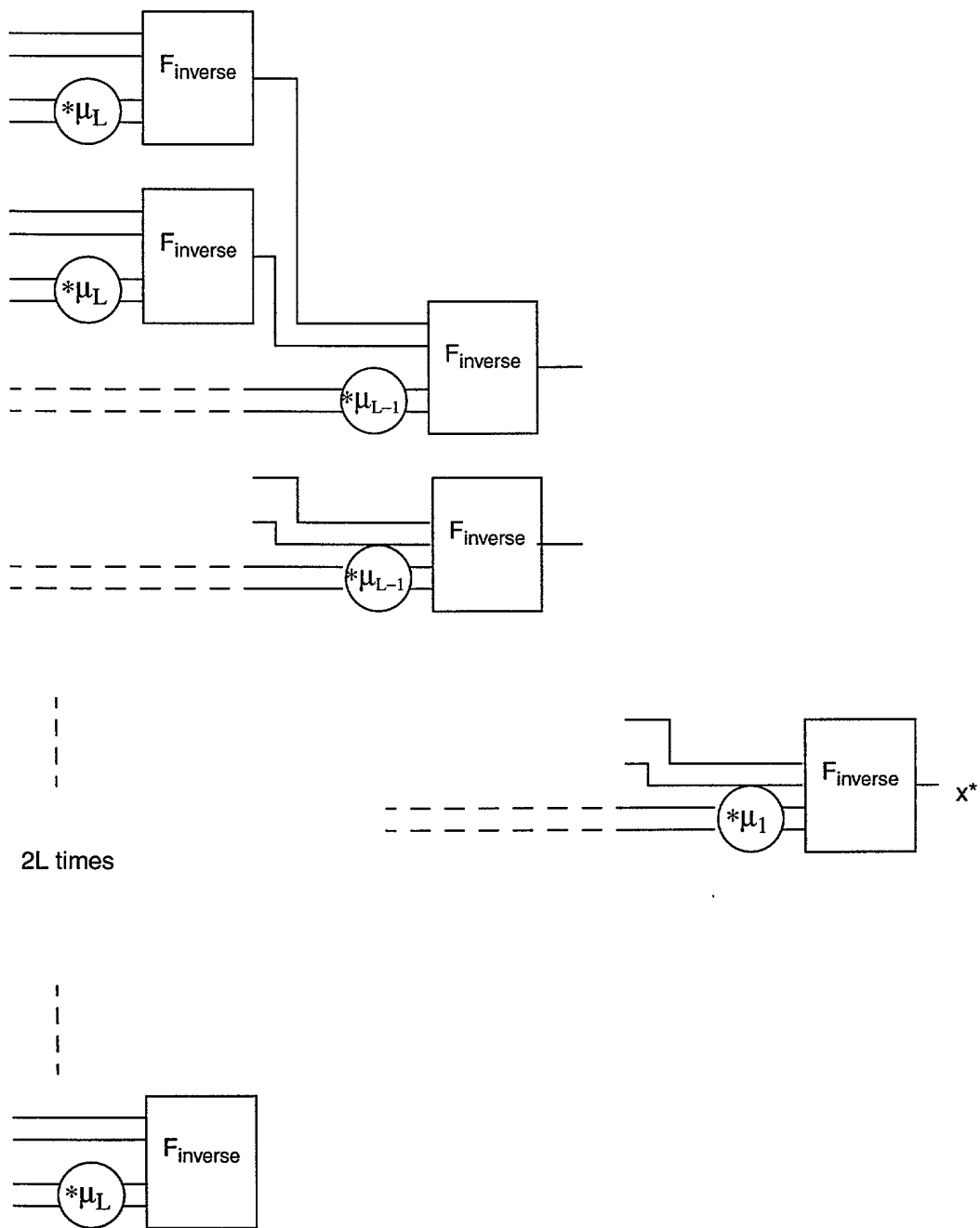


FIGURE 7D

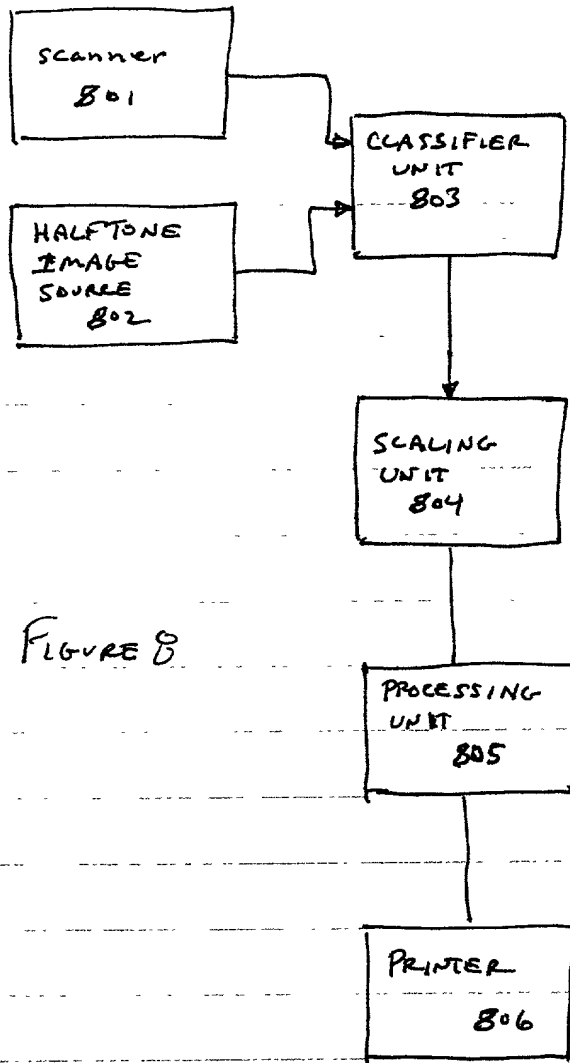


FIGURE 8

Patent

DECLARATION AND POWER OF ATTORNEY FOR PATENT APPLICATION

As a below named inventor, I hereby declare that:

My residence, post office address and citizenship are as stated below, next to my name.

I believe I am the original, first, and sole inventor (if only one name is listed below) or an original, first, and joint inventor (if plural names are listed below) of the subject matter which is claimed and for which a patent is sought on the invention entitled

"MULTISCALE SHARPENING AND SMOOTHING WITH WAVELETS"

the specification of which

X is attached hereto.
_____ was filed on _____ as
United States Application Number _____
or PCT International Application Number _____
and was amended on _____
(if applicable)

I hereby state that I have reviewed and understand the contents of the above-identified specification, including the claim(s), as amended by any amendment referred to above. I do not know and do not believe that the claimed invention was ever known or used in the United States of America before my invention thereof, or patented or described in any printed publication in any country before my invention thereof or more than one year prior to this application, that the same was not in public use or on sale in the United States of America more than one year prior to this application, and that the invention has not been patented or made the subject of an inventor's certificate issued before the date of this application in any country foreign to the United States of America on an application filed by me or my legal representatives or assigns more than twelve months (for a utility patent application) or six months (for a design patent application) prior to this application.

I acknowledge the duty to disclose all information known to me to be material to patentability as defined in Title 37, Code of Federal Regulations, Section 1.56.

I hereby claim foreign priority benefits under Title 35, United States Code, Section 119(a)-(d), of any foreign application(s) for patent or inventor's certificate listed below and have also identified below any foreign application for patent or inventor's certificate having a filing date before that of the application on which priority is claimed:

Prior Foreign Application(s)

Priority
Claimed

_____ (Number)	_____ (Country)	_____ (Day/Month/Year Filed)	_____ Yes	_____ No
_____ (Number)	_____ (Country)	_____ (Day/Month/Year Filed)	_____ Yes	_____ No
_____ (Number)	_____ (Country)	_____ (Day/Month/Year Filed)	_____ Yes	_____ No

I hereby claim the benefit under title 35, United States Code, Section 119(e) of any United States provisional application(s) listed below:

_____ (Application Number)	_____ Filing Date
_____ (Application Number)	_____ Filing Date

I hereby claim the benefit under Title 35, United States Code, Section 120 of any United States application(s) listed below and, insofar as the subject matter of each of the claims of this application is not disclosed in the prior United States application in the manner provided by the first paragraph of Title 35, United States Code, Section 112, I acknowledge the duty to disclose all information known to me to be material to patentability as defined in Title 37, Code of Federal Regulations, Section 1.56 which became available between the filing date of the prior application and the national or PCT international filing date of this application:

_____ (Application Number)	_____ Filing Date	_____ (Status -- patented, pending, abandoned)
_____ (Application Number)	_____ Filing Date	_____ (Status -- patented, pending, abandoned)

I hereby appoint the persons listed on Appendix A hereto (which is incorporated by reference and a part of this document) as my respective patent attorneys and patent agents, with full power of substitution and revocation, to prosecute this application and to transact all business in the Patent and Trademark Office connected herewith.

Send correspondence to Michael J. Mallie, **BLAKELY, SOKOLOFF, TAYLOR & ZAFMAN LLP**, 12400 Wilshire Boulevard 7th Floor, Los Angeles, California 90025 and direct telephone calls to Michael J. Mallie, (408) 720-8598.
(Name of Attorney or Agent)

I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code and that such willful false statements may jeopardize the validity of the application or any patent issued thereon.

Full Name of Sole/First Inventor Kathrin Berkner

Inventor's Signature _____ Date _____

Residence _____ (City, State) Citizenship _____ (Country)

Post Office Address _____

Full Name of Second/Joint Inventor _____

Inventor's Signature _____ Date _____

Residence _____ (City, State) Citizenship _____ (Country)

Post Office Address _____

Full Name of Third/Joint Inventor _____

Inventor's Signature _____ Date _____

Residence _____ (City, State) Citizenship _____ (Country)

Post Office Address _____

Full Name of Fourth/Joint Inventor _____

Inventor's Signature _____ Date _____

Residence _____ (City, State) Citizenship _____ (Country)

Post Office Address _____

APPENDIX A

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APPENDIX B

Title 37, Code of Federal Regulations, Section 1.56 Duty to Disclose Information Material to Patentability

(a) A patent by its very nature is affected with a public interest. The public interest is best served, and the most effective patent examination occurs when, at the time an application is being examined, the Office is aware of and evaluates the teachings of all information material to patentability. Each individual associated with the filing and prosecution of a patent application has a duty of candor and good faith in dealing with the Office, which includes a duty to disclose to the Office all information known to that individual to be material to patentability as defined in this section. The duty to disclosure information exists with respect to each pending claim until the claim is cancelled or withdrawn from consideration, or the application becomes abandoned. Information material to the patentability of a claim that is cancelled or withdrawn from consideration need not be submitted if the information is not material to the patentability of any claim remaining under consideration in the application. There is no duty to submit information which is not material to the patentability of any existing claim. The duty to disclose all information known to be material to patentability is deemed to be satisfied if all information known to be material to patentability of any claim issued in a patent was cited by the Office or submitted to the Office in the manner prescribed by §§1.97(b)-(d) and 1.98. However, no patent will be granted on an application in connection with which fraud on the Office was practiced or attempted or the duty of disclosure was violated through bad faith or intentional misconduct. The Office encourages applicants to carefully examine:

- (1) Prior art cited in search reports of a foreign patent office in a counterpart application, and
 - (2) The closest information over which individuals associated with the filing or prosecution of a patent application believe any pending claim patentably defines, to make sure that any material information contained therein is disclosed to the Office.
- (b) Under this section, information is material to patentability when it is not cumulative to information already of record or being made or record in the application, and
- (1) It establishes, by itself or in combination with other information, a prima facie case of unpatentability of a claim; or
 - (2) It refutes, or is inconsistent with, a position the applicant takes in:
 - (i) Opposing an argument of unpatentability relied on by the Office, or
 - (ii) Asserting an argument of patentability.

A prima facie case of unpatentability is established when the information compels a conclusion that a claim is unpatentable under the preponderance of evidence, burden-of-proof standard, giving each term in the claim its broadest reasonable construction consistent with the specification, and before any consideration is given to evidence which may be submitted in an attempt to establish a contrary conclusion of patentability.

(c) Individuals associated with the filing or prosecution of a patent application within the meaning of this section are:

- (1) Each inventor named in the application;
 - (2) Each attorney or agent who prepares or prosecutes the application; and
 - (3) Every other person who is substantively involved in the preparation or prosecution of the application and who is associated with the inventor, with the assignee or with anyone to whom there is an obligation to assign the application.
- (d) Individuals other than the attorney, agent or inventor may comply with this section by disclosing information to the attorney, agent, or inventor.

JC688 U.S. PTO
09/467544
12/10/99

EXPRESS MAIL CERTIFICATE OF MAILING

"Express Mail" mailing label number: EL431889769US

Date of Deposit: 12-10-99

I hereby certify that I am causing this paper or fee to be deposited with the United States Postal Service "Express Mail Post Office to Addressee" service on the date indicated above and that this paper or fee has been addressed to the Assistant Commissioner for Patents, Washington, D. C. 20231

Sharon M. Osofsky
(Typed or printed name of person mailing paper or fee)

Sharon M. Osofsky
(Signature of person mailing paper or fee)

12-10-99
(Date signed)

Serial/Patent No.: ***** Filing/Issue Date: *****
Client: Ricoh Corporation
Title: MULTISCALE SHARPENING AND SMOOTHING WITH WAVELETS

BSTZ File No.: 74451.P103
Date Mailed: December 10, 1999

Atty/Secty Initials: MJM/smo
Docket Due Date: *****

The following has been received in the U.S. Patent & Trademark Office on the date stamped hereon:

- | | | |
|--|--|--|
| <input type="checkbox"/> Amendment/Response (____ pgs.) | <input checked="" type="checkbox"/> Express Mail No. <u>EL431889769US</u> | Check No. <u>32175</u> |
| <input type="checkbox"/> Appeal Brief (____ pgs.) (in triplicate) | <input type="checkbox"/> _____ Month(s) Extension of Time | Amt: <u>\$2,362.00</u> |
| <input checked="" type="checkbox"/> Application - Utility (<u>55</u> pgs., with cover and abstract) | <input type="checkbox"/> Information Disclosure Statement & PTO-1449 (____ pgs.) | <input type="checkbox"/> Check No. _____ |
| <input type="checkbox"/> Application - Rule 1.53(b) Continuation (____ pgs.) | <input type="checkbox"/> Issue Fee Transmittal | Amt: _____ |
| <input type="checkbox"/> Application - Rule 1.53(b) Divisional (____ pgs.) | <input type="checkbox"/> Notice of Appeal | |
| <input type="checkbox"/> Application - Rule 1.53(b) CIP (____ pgs.) | <input type="checkbox"/> Petition for Extension of Time | |
| <input type="checkbox"/> Application - Rule 1.53(d) CPA Transmittal (____ pgs.) | <input type="checkbox"/> Petition for _____ | |
| <input type="checkbox"/> Application - Design (____ pgs.) | <input checked="" type="checkbox"/> Postcard | |
| <input type="checkbox"/> Application - PCT (____ pgs.) | <input type="checkbox"/> Power of Attorney (____ pgs.) | |
| <input type="checkbox"/> Application - Provisional (____ pgs.) | <input type="checkbox"/> Preliminary Amendment (____ pgs.) | |
| <input type="checkbox"/> Assignment and Cover Sheet | <input type="checkbox"/> Reply Brief (____ pgs.) | |
| <input checked="" type="checkbox"/> Certificate of Mailing | <input type="checkbox"/> Response to Notice of Missing Parts | |
| <input checked="" type="checkbox"/> Declaration & POA (____ pgs.) (Unsigned) | <input type="checkbox"/> Small Entity Declaration for Indep. Inventor/Small Business | |
| <input type="checkbox"/> Disclosure Docs & Orig. Copy of Inventor's Signed Letter (____ pgs.) | <input checked="" type="checkbox"/> Transmittal Letter, <u>XXXXXX</u> | |
| <input checked="" type="checkbox"/> Drawings: <u>11</u> # of sheets includes <u>14</u> figures | <input checked="" type="checkbox"/> Fee Transmittal, in duplicate | |
- ☐ Other: _____